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A DIGITAL COMPUTER PROGRAM FOR CALCULATING STEADY TEMPERATURE AND DENSITY DISTRIBUTIONS IN A GAS CONTAINING HEAT SOURCES

by Harry W. Davison

Lewis Research Center

Cleveland, Ohio

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A DIGITAL COMPUTER PROGRAM FOR CALCULATING STEADY TEMPERATURE AND DENSITY DISTRIBUTIONS IN A GAS CONTAINING HEAT SOURCES

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SUMMARY

A digital computer program that allows calculation of axial temperature and density distributions in a stagnant gas enclosed within an annulus is presented. The program, called STADDIG, is written in FORTRAN IV language for the IBM 7094 computer and is based on a steady-state one-dimensional (radial) heat-transfer calculation using cylindrical coordinates. The gas density is related to the gas temperature through the perfect gas law. The program allows for conduction across the gas and across the container walls. Heat is dissipated from the container walls by forced-convection cooling with an incompressible coolant. Heat sources are included in the coolant, the gas, and the container walls.

The axial distribution of gas temperature and density is determined by successive radial heat-transfer calculations at different axial positions. Axial heat conduction is neglected. A typical problem containing 20 axial increments requires about 4 seconds of running time when the gas densities and thermal conductivities are required to converge within 0.1 and 1 percent, respectively. Changing the convergence requirements has no appreciable influence on the problem running time.

INTRODUCTION

The determination of temperature and density distributions is a typical problem that arises when a neutron-absorbing gas in a nuclear reactor is exposed to a neutron flux. The spatial distribution of the mass of gas (gas density) must be known because of its influence on the spatial distribution of neutrons and the resulting effects on reactor criticality.

This report presents a method of determining the temperature and density distributions in a stagnant gas containing distributed heat sources. A digital computer program, called STADDIG, allows calculation of temperature and density distributions in a gas exposed to a neutron flux. The volumetric heating rates in the gas and the container walls are expressed as functions of the gas density and the neutron flux. The program STADDIG was used in the analysis of a helium 3 control system for a nuclear rocket reactor (ref. 1).

The mathematical models, including the basic assumptions and a summary of equations used in the computer program STADDIG, are discussed. Symbols are defined in appendix A; the basic equations are derived in appendix B. The computer program, including details of the input and output data, is discussed in appendix C; and a sample calculation, which demonstrates the preparation of the input data and shows the format of the output, is given in appendix D. Figure 1 contains a flow sheet for the computer program, including references to pertinent tables and equations.

DESCRIPTION OF MATHEMATICAL MODELS

The mathematical model provides a tool for calculating axial temperature and density distributions in a stagnant gas enclosed within an annulus formed by two concentric tubes, as illustrated in figure 2. Heat is generated in the gas and in the tube walls. The heat generated in the gas is produced in the exoergic reaction between the neutrons and the gas. The energy exists as kinetic energy of the reaction products. (Only two products are allowed in STADDIG.) As these reaction products or projectiles undergo collisions with the gas, energy is transferred to the gas. All neutron-gas reactions are assumed to occur at one neutron energy (that is, to be monoenergetic). The heat generated in the tubes has two sources: (1) the absorption of the remainder of the reaction product energy and (2) other heat-production reactions, which are assumed to be proportional to the neutron flux, such as neutron and gamma reactions in the metal. The gas and the tubes are cooled by an incompressible fluid flowing inside the inner tube and outside the outer tube. One-dimensional (radial) steady-state heat transfer is assumed in calculating a radially averaged gas temperature. The axial distribution of the radially averaged gas temperature is determined by successive radial heat-transfer calculations at different axial positions and includes the heat absorbed by the coolant. The axial gas density distribution, for a specified gas pressure, is calculated by the modified perfect-gas relation $p = z\rho\mathscr{R}T$ and by the radial gas temperature distribution.

The model has the following limitations:

(1) The volumetric heat-generation rates and the thermal conductivities for the gas and the metal tubes are independent of radial position.

(2) The radially averaged gas density is assumed to be inversely proportional to the radially averaged gas temperature.

(3) Heat is transferred through the gas to the tube walls by conduction only but is re-

moved from the tube walls by forced convection to an incompressible coolant.

(4) Heat conduction in the axial direction in the gas and the tubes is neglected.

The equations outlined below are incorporated in the computer program to calculate (1) the radially averaged gas temperature at any axial position, (2) the axial distribution of gas density, and (3) the total mass of gas enclosed in an annulus for any selected gas pressure.

Radially Averaged Gas Temperature

The radial temperature distribution through the gas is determined from the solution of the Poisson equation in cylindrical coordinates, with the azimuthal and axial dependence neglected. The following equations, are required to calculate the radially averaged gas temperature. Some of these equations are derived in appendix B.

$$\overline{T} = T_2 - \frac{q_g}{8k_g}\left(R_3^2 - R_2^2\right) + \frac{q_g}{4k_g}\left[\frac{R_3^2 \ln\left(\frac{R_3}{R_2}\right)^2}{R_3^2 - R_2^2} - 1\right]R_M^2 \tag{1}$$

$$T_2 = T_{b,I} + \frac{\left(R_M^2 - R_2^2\right)q_g + \left(R_2^2 - R_1^2\right)q_m}{2R_1 h_{b,I}} + \frac{\left[\left(R_M^2 - R_2^2\right)q_g + q_m R_2^2\right]\ln\frac{R_2^2}{R_1^2} - q_m\left(R_2^2 - R_1^2\right)}{4k_m} \tag{2}$$

(See eqs. (B10) and (B13).)

$$h_{b,I} = \frac{0.023\ Pr^{1/3}Re^{0.8}k}{D_e} \tag{3}$$

$$q_g = 1.602\times 10^{-13}\ \frac{EA_N\sigma\bar{\rho}_g S\varphi}{M} \tag{4}$$

$$q_m = K_s\varphi + \frac{(1 - S)\left(R_3^2 - R_2^2\right)}{S\left(R_2^2 - R_1^2 + R_4^2 - R_3^2\right)} q_g \tag{5}$$

(See eqs. (B21), (B22), and (B23).)

The thermal conductivity of the gas k_g is approximated by a linear function of the average gas temperature $\overline{T}$:

$$k_g = a + b\overline{T} \tag{6}$$

$$T_{b,I,j} = T_{b,I,(j-1)} + \frac{H_{b,I,j} + H_{g,I,j} + H_{m,I,j}}{vA\rho C_p} \tag{7}$$

The equation for R_M^2 is presented in appendix B (eq. (B14).)

Axial Distribution of Gas Density

The radially averaged gas density at any position is represented by the relation

$$\bar{\rho}_g = \frac{\int_{R_2}^{R_3} 2\pi r\rho_g \, dr}{\int_{R_2}^{R_3} 2\pi r \, dr} \tag{8}$$

The gas density is related to the gas temperature through the perfect gas law:

$$\rho_g = \frac{pM}{z\mathscr{R}T} \tag{9}$$

When the value of ρ_g from equation (9) is substituted into equation (8), the resulting integral is difficult to solve in closed form. However, for small radial perturbations in gas density or temperature, the average gas density can be approximated by

$$\bar{\rho}_g = \frac{pM}{z\mathscr{R}\overline{T}} \tag{10}$$

The average gas temperature $\overline{T}$, the average density $\bar{\rho}_g$, and the heat-generation rates q_g are related through equations (1) to (7), (10), and (B14). These equations are iteratively solved for a specific system pressure p to obtain the radially averaged gas density. The effect of the axial neutron flux distribution on gas temperature and density is transmitted through the heat-generation rates in the gas q_g, the tube walls q_m, and the coolant $H_{b,j}$. The axial distribution of the gas density is obtained by solving the preceding system of equations at successive axial positions, with different neutron fluxes but the same system pressures. The axial density distribution can be calculated for several different system pressures by inserting a pressure increment Δp_g and the number of pressures to be investigated (KOUNT) as input data. Each system pressure p_g is calculated from

$$p_g = p_{g,s} - \Delta p_k$$

where

$$\Delta p_k = (K - 1)\Delta p_g$$

and

$$1 \leq K \leq \text{KOUNT}$$

Total Mass of Gas

The total mass of gas in a single annulus W is

$$W = \Gamma \tau_c \tag{11}$$

The axially averaged gas density Γ is

$$\Gamma = \frac{\sum_{j=1}^{n} \bar{\rho}_j}{n} \tag{12}$$

The annulus volume τ_c is

$$\tau_c = \pi\left(R_3^2 - R_2^2\right)L \tag{13}$$

CONCLUDING REMARKS

A digital computer program called STADDIG written in FORTRAN IV language is presented. This program allows calculation of steady-state axial temperature and density distributions in a stagnant gas enclosed within an annular space between two concentric tubes. Variable heat generation in the axial direction is allowed in both the gas and the tubes. Heat is dissipated in the gas by conduction to the tubes. The tubes are cooled by forced convection to an incompressible fluid.

The program includes calculation of coolant temperature distributions, tube wall temperatures, friction pressure drop in coolant channels, and total mass of gas in an annulus.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, April 25, 1967,
122-28-02-04-22.

APPENDIX A

SYMBOLS

A cross-sectional area, cm^2

A_N Avogadro number

a constant used in correlation for k_g, $W/(cm)(^oK)$

b constant used in correlation for k_g, $W/(cm)(^oK^2)$

C arbitrary constant

C_p heat capacity, $W/(sec)(g)(^oK)$

C_5 coefficient used in empirical stopping power - energy correlation

C_6 exponent used in empirical stopping power - energy correlation

D_e equivalent diameter, cm

E energy released after absorbtion of neutron, MeV; J

f friction factor

G mass flow rate, g/sec

H heat-generation rate, W

h forced-convection heat-transfer coefficient, $W/(cm^2)(^oK)$

K proportionality constant, $W/(sec)(cm)$

k thermal conductivity, $W/(cm)(^oK)$

L length of gas annulus, cm

M molecular weight, g/mole

Nu Nusselt number

n number of axial increments

Pr Prandtl number

p pressure, N/cm^2

q volumetric heat-generation rate, W/cm^3

R specific radial field position, cm

ΔR gas tube wall thickness, cm

$\mathcal{R}$ universal gas constant, $N(cm)/(g)(mole)(^oK)$

Re Reynolds number

R_M radius at maximum temperature, cm

R_5 radius of fuel or, for annular cells, radius of tube surrounding outer tube forming gas annulus, cm

R_6 center-to-center spacing of gas-containing tubes, cm

r general radial field position, cm

S fraction of E absorbed in gas

T temperature, ^oK

v coolant velocity, cm/sec

W mass of gas in annulus, g

WP wetted perimeter, cm

X axial length, cm

ΔX increment of axial length, cm

z compressibility factor

β linear range of particle, cm

Γ axially averaged gas density, g/cm^3

μ viscosity, $g/(cm)(sec)$

ρ density, g/cm^3

$\bar{\rho}$ radially averaged density, g/cm^3

σ microscopic reaction cross section for neutrons, b; cm^2

τ volume, cm^3

φ neutron flux, neutrons/ $(cm^2)(sec)$

ψ range of particle, g/cm^2

Subscripts:

a portion of heating rate in tube walls due to absorption of reaction products

b bulk water conditions

c calculated values of density and conductivity

f average conditions in convective film

g average conditions in gas

I inner coolant channel

i estimated

j axial location

k pressure increment

M maximum

m tube material

o outer coolant channel

p, t reaction products produced in gas-neutron reaction

s initial condition

1, 2, 3, 4 inner and outer surfaces of inner and outer tubes forming annulus

γ portion of heating rate in tube walls that is proportional to φ

APPENDIX B

DERIVATION OF EQUATIONS

The equations used to calculate the radially averaged gas temperature in STADDIG are derived herein. The one-dimensional Poisson equation is used to calculate the radial temperature distribution through a stagnant gas containing heat sources and held in an annulus formed by two concentric tubes (fig. 2).

$$\frac{d^2T}{dr^2} + \frac{1}{r}\frac{dT}{dr} + \frac{q}{k} = 0 \qquad R_2 < r < R_3 \tag{B1}$$

$$T = -\frac{q}{k}\frac{r^2}{4} + C_1 \ln r + C_2 \tag{B2}$$

The boundary conditions are

$$T = T_2 \qquad \text{at } r = R_2$$

$$\frac{dT}{dr} = 0 \qquad \text{at } r = R_M$$

where R_M is the radius at maximum temperature. Inherent in the second boundary condition is the assumption that the radius of maximum temperature actually occurs in the gas ($R_3 > R_M > R_2$).

For certain coolant-flow distributions, the maximum temperature could occur in the wall of either tube rather than in the gas. Although the equations governing this situation are not derived herein, they are included in the computer program. The equations can be easily derived by the techniques presented herein.

The gas temperature at any radial position is

$$T = T_2 + \frac{q_g}{4k_g}\left(R_2^2 - r^2 + 2R_M^2 \ln \frac{r}{R_2}\right) \tag{B3}$$

The average gas temperature in the annulus is

$$\overline{T} = \frac{\int_{R_2}^{R_3} T(2\pi r\ dr)}{\int_{R_2}^{R_3} 2\pi r\ dr} \tag{B4}$$

$$\overline{T} = T_2 - \frac{q_g}{8k_g}\left(R_3^2 - R_2^2\right) + \frac{q_g}{4k_g}\left[\frac{R_3^2 \ln\left(\frac{R_3}{R_2}\right)^2}{R_3^2 - R_2^2} - 1\right] R_M^2 \tag{B5}$$

The variables R_M^2, T_2, q_g, and k_g must be determined. All other variables in equation (B5) are given in the statement of the problem to be solved.

The maximum temperature T_M is calculated as a function of R_M^2 and $T_{b,I}$ and as a function of R_M^2 and $T_{b,o}$. The two relations for T_M are equated, and the resulting equation is solved for R_M^2.

$$\left.\begin{aligned} T_M &= T_{b,I} + (T_M - T_2) + (T_2 - T_1) + (T_1 - T_{b,I}) \\ &= T_{b,o} + (T_M - T_3) + (T_3 - T_4) + (T_4 - T_{b,o}) \end{aligned}\right\} \tag{B6}$$

The term $T_M - T_2$ is determined by equation (B3).

$$(T_M - T_2) = \frac{q_g}{4k_g}\left(R_2^2 - R_M^2 + 2R_M^2 \ln \frac{R_M}{R_2}\right) \tag{B7}$$

The term $T_M - T_3$ is determined by using the following boundary conditions with equation (B2):

$$T = T_3 \qquad \text{at } r = R_3$$

$$\frac{dT}{dr} = 0 \qquad \text{at } r = R_M$$

$$(T_M - T_3) = \frac{q_g}{4k_g}\left(R_3^2 - R_M^2 + 2R_M^2 \ln \frac{R_M}{R_3}\right) \tag{B8}$$

The following boundary conditions were used with equation (B2) to solve for $T_2 - T_1$:

$$\left.\begin{aligned} T &= T_1 \qquad \text{at } R = R_1 \\ k_m \frac{dT}{dr} &= \frac{\left(R_M^2 - R_2^2\right)q_g}{2R_2} \qquad \text{at } r = R_2 \end{aligned}\right\} (R_1 < r < R_2)$$

The second boundary condition represents constant heat flux across the boundary between the gas and the inner tube.

$$T = T_1 + \frac{q_m}{4k_m}\left(R_1^2 - r^2\right) + \left[\frac{\left(R_M^2 - R_2^2\right)q_g}{2k_m} + \frac{q_m R_2^2}{2k_m}\right]\ln \frac{r}{R_1} \tag{B9}$$

$$(T_2 - T_1) = \frac{q_m}{4k_m}\left(R_1^2 - R_2^2\right) + \left[\frac{\left(R_M^2 - R_2^2\right)q_g + q_m R_2^2}{2k_m}\right]\ln \frac{R_2}{R_1} \tag{B10}$$

The temperature difference $T_3 - T_4$ is determined from

$$\left.\begin{aligned} T &= T_4 \qquad \text{at } r = R_4 \\ k_m \frac{dT}{dr} &= \frac{\left(R_M^2 - R_3^2\right)q_g}{2R_3} \qquad \text{at } r = R_3 \end{aligned}\right\} (R_3 < r < R_4)$$

The second boundary condition represents constant heat flux across the boundary between the gas and the outer tube.

$$T = T_4 + \frac{q_m}{4k_m}\left(R_4^2 - r^2\right) + \left[\frac{\left(R_M^2 - R_3^2\right)q_g}{2k_m} + \frac{q_m R_3^2}{2k_m}\right]\ln \frac{r}{R_4} \tag{B11}$$

$$(T_3 - T_4) = \frac{q_m}{4k_m}\left(R_4^2 - R_3^2\right) + \left[\frac{\left(R_M^2 - R_3^2\right)q_g}{2k_m} + \frac{q_m R_3^2}{2k_m}\right]\ln\frac{R_3}{R_4} \tag{B12}$$

The temperature rise across the outer and inner convective coolant films $T_4 - T_{b,o}$ and $T_1 - T_{b,I}$ are determined by a heat balance:

$$\left.\begin{aligned}(T_4 - T_{b,o}) &= \frac{\left(R_3^2 - R_M^2\right)q_g + \left(R_4^2 - R_3^2\right)q_m}{2R_4 h_{b,o}} \\ (T_1 - T_{b,I}) &= \frac{\left(R_M^2 - R_2^2\right)q_g + \left(R_2^2 - R_1^2\right)q_m}{2R_1 h_{b,I}}\end{aligned}\right\} \tag{B13}$$

Substituting equations (B7), (B8), (B10), (B12), and (B13) into equation (B6) and solving for R_M^2 yield

$$R_M^2 = \frac{(T_{b,o} - T_{b,I}) + B_5 q_m + B_6 q_g}{\frac{q_g}{4k_g}\left[\ln\left(\frac{R_3}{R_2}\right)^2 + \frac{k_g}{k_m}\ln\left(\frac{R_4 R_2}{R_1 R_3}\right)^2 + 2k_g\left(\frac{1}{R_4 h_{b,o}} + \frac{1}{R_1 h_{b,I}}\right)\right]} \tag{B14}$$

where

$$B_5 = \frac{\left(R_4^2 - R_3^2 - R_3^2 \ln\frac{R_4^2}{R_3^2}\right) + \left(R_2^2 - R_1^2 - R_2^2 \ln\frac{R_2^2}{R_1^2}\right)}{4k_m} + \frac{R_4^2 - R_3^2}{2R_4 h_{b,o}} - \frac{R_2^2 - R_1^2}{2R_1 h_{b,I}}$$

and

$$B_6 = \frac{R_3^2 - R_2^2}{4k_g} - \frac{R_3^2 \ln\frac{R_3^2}{R_4^2} - R_2^2 \ln\frac{R_2^2}{R_1^2}}{4k_m} + \frac{R_2^2}{2R_1 h_{b,I}} + \frac{R_3^2}{2R_4 h_{b,o}}$$

Forced-Convection Film Coefficient

The Colburn equation (ref. 2) was used to approximate the forced-convection film coefficients for both the inside and outside coolant channels:

$$Nu_f = 0.023\ Pr^{1/3}Re^{0.8}$$

$$h = \frac{0.023\ Pr^{1/3}Re^{0.8}k}{D_e} \tag{B15}$$

Volumetric Heat-Generation Rate in Gas

When the gas absorbs a neutron, an unstable intermediate product may be formed. This unstable intermediate product decomposes into two secondary recoil products (only two recoil products are allowed in the computer program). Heat is generated in the gas as the result of the slowing down of the recoil products. The volumetric heat-generation rate q_g is determined from (1) the calculated reaction rate between the gas and the neutrons, (2) the energy released in each reaction, and (3) the fraction of energy absorbed in the gas.

$$q_g = 1.602\times10^{-13}\ \frac{EA_N\sigma\bar{\rho}_g S\varphi}{M} \tag{B16}$$

The values of E, σ, φ, and M must be specified as input data for the calculation. The fraction of the energy absorbed in the gas S may be either specified as input data or calculated.

If S is to be calculated, the program incorporates the model proposed in reference 1. In this model it is assumed that the average distance a projectile travels $\bar{\beta}$ in an annulus is the radius of a sphere whose volume is equal to the volume in which a projectile can be stopped in an annulus:

$$\bar{\beta} = \left[\frac{\frac{3}{4}\psi(R_3 - R_2)\left(R_3^2 - R_2^2\right)^{1/2}}{\rho_g}\right]^{1/3} \tag{B17}$$

The energy lost by the reaction products while slowing down in the gas is determined by integrating an empirical approximation for the stopping powers $dE/d(\rho_g \bar{\beta})$ of each projectile. The following stopping-power approximation is used in the program:

$$\frac{dE}{d\bar{\beta}} = -C_5 \rho_g E^{C_6} \tag{B18}$$

Integration of equation (B18) yields

$$E_s^{1-C_6} - E^{1-C_6} = C_5(1 - C_6)\rho_g \bar{\beta} \tag{B19}$$

where E_s is the initial energy of the projectile.

The fraction S of the energy deposited in the gas is

$$S = \frac{(E_s - E)_p + (E_s - E)_t}{E_{s,p} + E_{s,t}} \tag{B20}$$

The subscripts p and t refer to the two reaction products. The initial energy of the projectiles is specified as input data. The final energies of the projectiles are obtained from equation (B19).

Volumetric Heat-Generation Rate in Tube Walls

Heat is generated in the tube walls and is dissipated at the wall surface by forced convection. Two types of volumetric heat sources are provided. The first q_γ is proportional to neutron flux (e.g., heating due to absorbtion of primary gamma photons):

$$q_\gamma = K\varphi \tag{B21}$$

The second q_a results from absorption of the portion of the reaction products or projectiles that is not absorbed in the gas:

$$q_a = \frac{q_g(1 - S)\left(R_3^2 - R_2^2\right)}{S\left(R_2^2 - R_1^2 + R_4^2 - R_3^2\right)} \tag{B22}$$

where q_g is obtained from equation (B16) and S is obtained from equation (B20).

The total volumetric heating rate in the tube walls is

$$q_m = q_\gamma + q_a \tag{B23}$$

Coolant Temperature

The axial distribution of coolant temperature must be determined before the gas temperature and density can be determined. The coolant temperature at each elevation is calculated from the preceding coolant temperature, the power generation at each section, and the coolant flow rate:

$$T_{b,j} = T_{b,(j-1)} + \frac{H_{b,j} + H_{g,j} + H_{m,j}}{GC_{p,b}} \tag{B24}$$

The heat generated in the coolant is

$$\left.\begin{aligned} H_{b,j} &= \bar{q}_b A_o \, \Delta X \frac{\varphi}{\bar{\varphi}} \qquad \text{when } r > R_4 \\ H_{b,j} &= \bar{q}_b A_I \, \Delta X \frac{\varphi}{\bar{\varphi}} \qquad \text{when } r < R_1 \end{aligned}\right\} \tag{B25}$$

where $\varphi/\bar{\varphi}$ is the relative neutron flux at any axial location.

At any axial location j, the heat-generation rates in the gas in the regions inside $(H_{g,j,I})$ and outside $(H_{g,j,o})$ the radius of maximum temperature are

$$\left.\begin{aligned} &H_{g,j,I} = \pi q_g \, \Delta X\left(R_M^2 - R_2^2\right) \qquad \text{when } R_2 < r < R_M \\ &\text{and} \\ &H_{g,j,o} = \pi q_g \, \Delta X\left(R_3^2 - R_M^2\right) \qquad \text{when } R_3 > r > R_M \end{aligned}\right\} \tag{B26}$$

The heat-generation rates in the inner and outer tubes are

$$H_{m,j} = \pi q_m \Delta X\left(R_2^2 - R_1^2\right) \qquad \text{when } R_1 < r < R_2$$

and (B27)

$$H_{m,j} = \pi q_m \Delta X\left(R_4^2 - R_3^2\right) \qquad \text{when } R_4 > r > R_3$$

The coolant physical properties are assumed to be constant along the length of the tubes.

Equivalent Diameters of Coolant Channels

The equivalent diameter D_e of a channel is defined as four times the cross-sectional flow area A, divided by the wetted perimeter WP. The equivalent diameter D_e of the inner channel is the diameter of the inner tube. The equivalent diameter of the outer channel depends on the lattice geometry in which the tube is located. Any of three separate geometries is permitted in this program: square, equilateral triangular, or annular. These geometries are illustrated in figure 3. For the first two geometries, the gas annulus is located at the center of the cell surrounded by other cylindrical tubes, such as fuel elements. In the annular geometry, the outer tube of the gas annulus is concentric with the larger tube that surrounds it. Equations for cross-sectional flow area A, wetted perimeter WP, and equivalent diameter D_e are given in table I.

The lattice geometry is selected in the computer program by inserting the appropriate value of RG, as indicated in appendix C.

TABLE I. - TUBE GEOMETRY

Geometry	Equation for -			Figure
	Cross-sectional area, A, cm^2	Wetted perimeter, WP, cm	Equivalent diameter, D_e, cm	
Equilateral triangle	$1.299\ R_6^2 - \frac{\pi}{2}\left(R_5^2 + 2R_4^2\right)$	$\pi(R_5 + 2R_4)$	$\dfrac{5.196\ R_6^2 - 2\pi\left(R_5^2 + 2R_4^2\right)}{\pi(R_5 + 2R_4)}$	4(a)
Square	$R_6^2 - \pi\left(R_5^2 + R_4^2\right)$	$2\pi(R_5 + R_4)$	$\dfrac{2R_6^2 - 2\pi\left(R_5^2 + R_4^2\right)}{\pi(R_5 + R_4)}$	4(b)
Annular	$\pi\left(R_5^2 - R_4^2\right)$	$2\pi(R_5 + R_4)$	$2(R_5 - R_4)$	4(c)

Friction Pressure Drop in Coolant Channels

The irreversible pressure loss in the inner and outer coolant channels was calculated by the Fanning equation for isothermal flow (ref. 3):

$$\Delta p = \frac{2fLv^2\rho_b}{D_e} \tag{B28}$$

$$v = \frac{G}{\rho_b A} \tag{B29}$$

The friction factor f is approximated by

$$f = 0.046\ Re^{-0.2} \tag{B30}$$

where Re is the Reynolds number. This friction-factor correlation is valid for fluids flowing in smooth tubes and for Reynolds numbers between 10^4 and 10^5.

APPENDIX C

DESCRIPTION OF COMPUTER PROGRAM

The axial distribution of gas temperatures and densities and the total mass of gas in an annulus are calculated by equations (10) to (13) and (B14). The only iterative procedures in the computer program are associated with the determination of the radially averaged gas density and the thermal conductivity of the gas. The initial estimate of the gas density is 1 milligram per cubic centimeter. All density dependent variables, including average gas temperature, are calculated by using this initial guess. The density $\rho_{g,c}$ is calculated (eq. (10)) from the temperature, the pressure, the molecular weight, and the compressibility of the gas and is compared with the estimated value. The absolute values of the fractional difference between estimated and calculated values of density are compared with a convergence parameter CONV1 which is part of the input data. When

$$\left|\frac{\rho_{g,c} - \rho_{g,i}}{\rho_{g,i}}\right| > \mathrm{CONV1}$$

a new value of the density is estimated and the calculations are repeated. If the result is equal to or less than the convergence parameter, the solution is accepted, and a calculation is initiated for the next axial increment.

The initial estimate of the thermal conductivity of the gas $k_{g,i}$ is supplied as input data. This value is used to calculate the average gas temperature at any axial location. A new thermal conductivity $k_{g,c}$ is calculated by using equation (6) and the average gas temperature. The absolute value of the fractional difference between calculated and estimated conductivity is compared with another convergence parameter CONV2, which is part of the input data. When

$$\left|\frac{k_{g,c} - k_{g,i}}{k_{g,i}}\right| > \mathrm{CONV2}$$

a new value of $k_{g,i}$ is estimated, and the calculation is repeated until

$$\left|\frac{k_{g,c} - k_{g,i}}{k_{g,i}}\right| \leq \mathrm{CONV2}$$

The values of CONV1 and CONV2 were varied between 10^{-1} and 10^{-5} to determine their effect on problem running time. The maximum variation in problem running time, when only the convergence parameters were varied, was 3 to 5 seconds.

The input data for each problem require no fewer than 10 or 12 cards, depending on the option chosen for calculating the fraction of the total reaction product energy deposited in the gas. The input and output variables and options and the input data format are described in the two lists that follow. The character immediately following the FORTRAN variable name is the algebraic character used in the preceeding equations.

Input

Card	FORTRAN variable	Algebraic character	Format	Description	Units
1			72H	Problem title	
2	WGAM	q_b	F10.5	Average heating rate in coolant	W/cm^3
	FLOW1	G_I	F10.5	Coolant mass flow rate to inner channel	g/sec
	FLOW2	G_o	F10.5	Coolant mass flow rate to outer channel	g/sec
	DIST	L	F10.5	Total length of gas annulus	cm
	CONM	k_m	F10.5	Thermal conductivity of tube walls	$W/(cm)(^oK)$
	CONG	k_g	F10.5	Thermal conductivity of gas	$W/(cm)(^oK)$
3	RAD2	R_2	F10.5	Inner radius of annulus	cm
	RAD3	R_3	F10.5	Outer radius of annulus	cm
	DELR	ΔR	F10.5	Thickness of tube walls	cm
	PRESS	p_g	F10.5	Gas system pressure	N/cm^2
	DELP	Δp	F10.5	Pressure increment to be investigated	N/cm^2

Card	FORTRAN variable	Algebraic character	Format	Description	Units
	RG	----	F10.5	Option chosen to select proper lattice geometry Options RG Geometry 1.0 square 2.0 annular 3.0 triangular	-------------
4	SIGMAG	σ	F10.5	Microscopic reaction cross section for neutrons	b
	ATOMWT	M_g	F10.5	Molecular weight of gas	g/mole
	TB1	$T_{b,I}$	F10.5	Coolant inlet temperature for inner channel	^oK
	TB2	$T_{b,o}$	F10.5	Coolant inlet temperature for outer channel	^oK
	CODE	----	F10.5	Constant which must be 1.0	-------------
5	EPSOG	E	F10.5	Kinetic energy of reaction recoil particles	MeV/reaction
	RAD5	R_5	F10.5	Outer radius of cylindrical element (fig. 3) or, for annular cell geometry, inner radius of tube surrounding gas-filled tube	cm
	RAD6	R_6	F10.5	Center-to-center spacing of gas-containing tubes	cm

Card	FORTRAN variable	Algebraic character	Format	Description	Units
	SPLIT	S	F10. 5	Fraction of total energy produced in neutron-gas reaction that is absorbed in gas	-------------
	CHOICE	----	F10. 5	Option chosen to select method of determining SPLIT Options CHOICE — Method of determining SPLIT 1.0 — use value supplied in card 5 (SPLIT) 0.0 — calculate using model described previously	-------------
6	CON5	q_m	E10. 5	Average volumetric heat-generation rate in tube walls	W/cm^3
	AFLUX	$\overline{\varphi}$	E10. 5	Average thermal neutron flux	$\frac{\text{neutrons}}{(\text{cm}^2)(\text{sec})}$
7	IPEAK	----	I3	Estimated position of maximum flux (any number between 1 and MM)	-------------
	MM	n	I3	Number of axial increments to be investigated	-------------
	KOUNT	----	I3	Number of pressure values to be investigated	-------------

Card	FORTRAN variable	Algebraic character	Format	Description	Units
8	RHOC	ρ_b	F10.5	Coolant density	g/cm^3
	VISC	μ_b	F10.5	Coolant viscosity	g/(cm)(sec)
	CONDC	k_b	F10.5	Coolant thermal conductivity	$W/(cm)(^oK)$
	CAPC	$C_{p,b}$	F10.5	Coolant heat capacity	$(W)(sec)/(g)(^oK)$
9	ACON	a	E10.5	Empirical constant for linear fit of gas thermal conductivity	$W/(cm)(^oK)$
	BCON	b	E10.5	Empirical coefficient for linear fit of gas thermal conductivity	$W/(cm)(^oK^2)$
	ZCON	z	E10.5	Compressibility factor for gas	-------------
	CONV1	----	E10.5	Convergence parameter for gas density	-------------
	CONV2	----	E10.5	Convergence parameter for gas thermal conductivity	-------------
[a]10	BFLUX (I)	φ	(20X, E16.8)	Relative thermal neutron flux at axial position j	-------------

The following two cards must be supplied when SPLIT is to be calculated (CHOICE = 0.0), but must be omitted when CHOICE = 1.0.

Card	FORTRAN variable	Algebraic character	Format	Description	Units
11	RAEXPP	$C_{6,p}$	E10.4	Exponent used in empirical correlation between stopping power and range for particle p	-------------
	RAEXPT	$C_{6,t}$	E10.4	Exponent used in empirical correlation between stopping power and range for particle t	-------------

[a]One card is required for each value of thermal neutron flux.

Values for MM of the flux must be provided.

Card	FORTRAN variable	Algebraic character	Format	Description	Units
	RACOFP	$C_{5,P}$	E10.4	Coefficient used in empirical correlation between stopping power and range for particle p	-------------
	RACOFT	$C_{5,t}$	E10.4	Coefficient used in empirical correlation between stopping power and range for particle t	-------------
12	RANGP	ψ_p	E10.4	Range of particle p	g/cm^2
	RANGT	ψ_t	E10.4	Range of particle t	g/cm^2
	EOPRO	$E_{s,p}$	E10.4	Initial kinetic energy of particle p	MeV
	EOTRI	$E_{s,t}$	E10.4	Initial kinetic energy of particle t	MeV

Output

Line	FORTRAN variable	Algebraic character	Format	Description	Units
1 to 3	List of input data from cards 1 to 3				
4	List of input data from card 4 Length of each axial increment in centimeters (DELX)				
5	List of input data from card 5				
6	CON4	----	-----	Average energy production per unit of volume per unit of gas density due to neutron interaction with gas	$\frac{(W/cm^3)}{(g/cm^3)}$

Card	FORTRAN variable	Algebraic character	Format	Description	Units
List of input data from card 6					
7 to 9					
List of input data from cards 7 to 9					
[b]10 to 12					
List of input fluxes from cards 10 to MM					
13 and 14					
List of input data from cards 13 and 14					
[b]15 to 17					
List of input fluxes normalized to average neutron flux					
18	MASS	W	-----	Total mass of gas in annulus	g
19	PRESS	p_g	-----	Total gas pressure	N/cm^2
	AVG DENSITY	Γ	-----	Average gas density in annulus	g/cm^3
	RAD2	R_2	-----	Inner radius of annulus	cm
	GRADIENT	----	-----	Ratio of maximum gas density in annulus to minimum gas density	-------------
20	VEL(IN)	V_I	-----	Coolant velocity in inner coolant channel	cm/sec
	VEL(OUT)	V_o	-----	Coolant velocity in outer coolant channel	cm/sec
	FILMH1	h_1	-----	Forced-convective film coefficient in inner channel	$W/(cm^2)(^oK)$
	FILMH2	h_o	-----	Forced-convective film coefficient in outer channel	$W/(cm^2)(^oK)$
21	Q2(METAL)	----	-----	Total volumetric heat-generation rate of metal in stage MM	W/cm^3

[b]Greater or fewer lines may be required depending on number of axial increment (MM) required.

Card	FORTRAN variable	Algebraic character	Format	Description	Units
	QGAM	----	-----	Portion of Q2(METAL) not due to attenuation of recoil particles in stage MM	W/cm^3
	QP+T	----	-----	Portion of Q2(METAL) due to attentuation of recoil particles in stage MM	W/cm^3
	Q1(INGAS)	----	-----	Volumetric heat-generation rate of gas in stage MM	W/cm^3
	IMINRO	----	-----	Axial location of minimum gas density	-------------
	IMAXRO	----	-----	Axial location of maximum gas density	-------------
	PDRP1	Δp_I	-----	Irreversible (friction) pressure loss in inner coolant channel	N/cm^2
	PDRP2	Δp_o	-----	Irreversible (friction) pressure loss in outer channel	N/cm^2
23	REYIN	Re_I	-----	Reynolds number in inner channel	-------------
	REYOT	Re_o	-----	Reynolds number in outer channel	-------------

Tabular listing:

	ELEVATION	----	-----	Axial distance	cm
	DENSITY	ρ_g	-----	Average gas density	g/cm^3
	AVG TEMP	$\overline{T}_g$	-----	Average gas temperature	^oK

FORTRAN variable	Algebraic character	Format	Description	Units
MAX TEMP	T_M	-----	Maximum gas temperature	^oK
RMAX	R_M	-----	Radius at maximum temperature	cm
TBULK(IN)	$T_{b,I}$	-----	Bulk coolant temperature in inner coolant channel	^oK
TBULK(OUT)	$T_{b,o}$	-----	Bulk coolant temperature in outer coolant channel	^oK
TWALLM1	----	-----	Maximum temperature of inner tube wall	^oK
TWALLM2	----	-----	Maximum temperature of outer tube wall	^oK

APPENDIX D

SAMPLE CALCULATION

A sample problem and its solution are presented to demonstrate the preparation of input data for use in STADDIG and to illustrate the program output format. Because, in this sample problem, preparation of data and output format are emphasized, the accuracy of the data and the assumptions is of secondary importance. Therefore, the results should not be construed as an exact solution of the problem presented.

Problem

A nuclear reactor is controlled with helium 3 as a neutron poison. The helium 3 is contained in an annulus between two concentric aluminum tubes (fig. 4) which are cooled by water flowing inside the inner tube and outside the outer tube. Heat is generated from the ${}_2He^3(n, p){}_1T^3$ reaction at a rate of 0.765 MeV (1.22×10^{-13} J) per reaction. The sample problem is to determine the axial temperature and density distribution of helium 3 and the total mass of helium 3 held in an annulus, when the system is pressurized to 41 newtons per square centimeter.

The average thermal neutron flux in the reactor is 1.5×10^{15} neutrons per square centimeter per second, and the axial flux distribution is shown in figure 5. The neutrons are assumed to be monoenergetic; therefore, all reactions are thermal. The tube dimensions and the properties of helium 3, aluminum, and water are shown in table II. The average heating rates in the aluminum and water are 121 and 150 watts per cubic centimeter, respectively. The water mass flow rates to the inner and outer channels are 190 and 400 grams per second, respectively, and the inlet water temperature is 365° K. The range-energy relations for the protons and tritons were approximated by using the empirical relation in the program. The values of C_5 and C_6 were obtained empirically by plotting the range-energy data for protons in helium 4 (ref. 4) and by correcting the range using the Bragg-Kleeman rule (ref. 5). The same constants were used for the protons and the tritons. The values used for the coefficients and the exponents in the range-energy correlation were 276 and -0.75, respectively.

The cylindrical fuel assemblies have an outer diameter of 7.0 centimeters and are placed in a triangular pattern. The gas-containing tubes are located in the interstices between fuel elements, as shown in figure 4. The center-to-center spacing of the tubes is 4.6 centimeters.

TABLE II. - DATA FOR SAMPLE PROBLEM

Tube dimensions, cm	
Outer-tube inside diameter	1.940
Inner-tube outside diameter	1.740
Wall thickness	0.15
Tube length	107
Helium 3 properties	
Microscopic absorbtion cross section,[a] b	5400
Molecular weight, g	3.0
Thermal conductivity,[b] a + bT	
a, W/(cm)(°K)	0.865×10^{-3}
b, W/(cm)(°K^2)	0.321×10^{-5}
Compressibility factor[c]	1.0
Range of proton,[d] g/cm^2	0.755×10^{-3}
Range of triton,[d] g/cm^2	0.866×10^{-4}
Initial kinetic energy of proton,[e] MeV (J)	0.573 (0.914×10^{-13})
Initial kinetic energy of triton,[e] MeV (J)	0.191 (0.306×10^{-13})
Aluminum properties	
Thermal conductivity,[f] W/(cm)(°K)	1.989
Water properites[f]	
Density, g/cm^3	0.948
Viscosity, g/(cm)(sec)	0.26×10^{-2}
Thermal conductivity, W/(cm)(°K)	0.68×10^{-2}
Heat capacity, (W)(sec)/(g)(°K)	4.186

[a]Ref. 4.
[b]Values of constants are based on linear fit of corrected conductivity data from ref. 2. Conductivity of helium isotopes was assumed to be proportional to square root of their atomic weights, as proposed in ref. 5.
[c]Ref. 6.
[d]Ref. 7.
[e]Ref. 1.
[f]Ref. 2.

Solution

The variables given in the statement of the problem are presented in the appropriate system of units for use in the computer program. The input data are shown in table III. The options, RG = 3.0 and CHOICE = 0.0, were selected to permit (1) selection of triangular spacing and (2) calculation of the fraction of energy deposited in the gas. The convergence criterion selected for the radially averaged gas density and the thermal conductivity of the gas are 0.1 and 1 percent, respectively.

The computer output for the problem is given in table IV. The average and maximum gas temperatures, the inner and outer tube temperatures, and the coolant temperatures

TABLE III. - INPUT FORMAT FOR IBM 7094 COMPUTER PROGRAM

TITLE	PROJECT NUMBER	ANALYST	
SAMPLE PROBLEM INPUT DATA			SHEET ____ OF ____

STATEMENT NUMBER | CONT | FORTRAN STATEMENT | IDENTIFICATION

```
 STEADY TEMPERATURE AND DENSITY DISTRIBUTION IN A GAS WITH HEAT SOURCES
   150.0     190.0      400.0      107.0      1.989      0.0026
  0.870     0.970      0.150       41.0       1.5        3.0
  5400.0    3.0        365.0      365.0       1.0
  0.764     3.50       4.60       0.37        0.0
0.1212E+03   1.5E+15
  10 21   1
0.9483      0.0026     0.0068     4.1860
0.8650E-03 0.321E-05 1.000E+00 1.000E-03 1.000E-02
                         0.7869E+00
                         0.7258E+00
                         0.8528E+00
                         0.9545E+00
                         1.0528E+00
                         1.1337E+00
                         1.2017E+00
                         1.2513E+00
                         1.2846E+00
                         1.2993E+00
                         1.2965E+00
                         1.2753E+00
                         1.2360E+00
                         1.1779E+00
                         1.1037E+00
```

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TABLE III. - Concluded. INPUT FORMAT FOR IBM 7094 COMPUTER PROGRAM

TITLE	PROJECT NUMBER	ANALYST	
SAMPLE PROBLEM INPUT DATA			SHEET ____ OF ____

STATEMENT NUMBER	CONT	FORTRAN STATEMENT	IDENTIFICATION
1 2 3 4 5	6	7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72	73 74 75 76 77 78 79 80

```
                        1.0130E+00
                        0.9090E+00
                        0.7890E+00
                        0.6629E+00
                        0.5093E+00
                        0.4858E+00
-0.75E+00 -0.75E+00 0.276E+03 0.276E+03
0.755E-03 0.866E-04 0.573E+00 0.191E+00
```

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 | 73 74 75 76 77 78 79 80

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TABLE IV. - INPUT AND OUTPUT FOR SAMPLE PROBLEM

```
INPUT DATA
STEADY TEMPERATURE AND DENSITY DISTRIBUTION IN A GAS  WITH HEAT SOURCES

WGAMMA=150.00     FLOW1=   190.0     FLOW2=   400.0     DIST= 107.0     CONM=   1.989     CONG=   0.0026

RAD2=     0.8700     RAD3=     0.9700     DELR=  0.150000     PRESS=   41.0     DELP=  1.5     RG=   3.0

SIGMAG=   5400.00     ATOMWT=      3.00     TB1= 365.0     TB2= 365.0     CODE=1.0     DELX=  5.10

     EPSOG=    0.7640     RAD5=    3.5000     RAD6=    4.6000     SPLIT=    0.3700     CHOICE=  0.

CON4=0.1991E 06     CON5=0.1212E 03     AFLUX=.15000E 16

IPEAK= 10     NO OF INCREMENTS= 21     KOUNT=  1

     RHOC=     0.9483     VISC=     0.0026     CONDC=     0.0068     CAPC=     4.1860

     ACON=0.8650E-03     BCON=0.3210E-05     ZCON=0.1000E 01     CONV1=0.1000E-02     CONV2=0.1000E-01

FLUX=    0.7869    0.7258    0.8528    0.9545    1.0528    1.1337    1.2017    1.2513    1.2846    1.2993
   1.2965    1.2753    1.2360    1.1779    1.1037    1.0130    0.9090    0.7890    0.6629    0.5093
   0.4858

     RAEXPP= -0.7500E 00     RAEXPT= -0.7500E 00     RACOFP=  0.2760E 03     RACOFT=  0.2760E 03

     RANGP=0.7550E-03     RANGT=0.8660E-04     EOPRO=0.5730E 00     EOTRI=0.1910E 00

                    ***CALCULATIONS***

NORMALIZED FLUX

FLUX=    0.7868    0.7257    0.8527    0.9545    1.0527    1.1336    1.2016    1.2512    1.2845    1.2992
   1.2963    1.2751    1.2359    1.1778    1.1036    1.0129    0.9089    0.7890    0.6628    0.5093
   0.4858

MASS=  0.021673

     PRESS=   41.00     AVG.DENSITY=350407E-03     RAD2=  0.870000     GRADIENT=1.11461

VEL(IN)= 123.0     VEL(OUT)=  98.0     FILMH1=    0.90678     FILMH2=    0.82076

Q2(METAL)=679521E 02     QGAM=588787E 02     QP+T=907335E 01     Q1(INGAS)=616990E 01

IMINRO= 14     IMAXRO=  1     PORP1=.107E 00     PORP2=.116E 00

REYIN=.65549E 05     REYOT=.34673E 05
```

TABLE IV - Concluded. INPUT AND OUTPUT FOR SAMPLE PROBLEM

AXIAL DISTRIBUTION OF RMAX ,TEMPERATURES AND DENSITIES

ELEVATION CMS	DENSITY GMS/CC	AVG.TEMP KELVIN	MAX TEMP KELVIN	RMAX CMS	TBULK(IN) KELVIN	TBULK(OUT) KELVIN	TWALLM1 KELVIN	TWALLM2 KELVIN
5.1	0.3772E-03	392.5	394.8	0.91727	366.8	366.9	388.6	387.3
10.2	0.3772E-03	392.2	394.4	0.91747	368.4	368.6	388.5	387.5
15.3	0.3717E-03	398.2	400.6	0.91754	370.4	370.7	393.9	392.7
20.4	0.3670E-03	403.4	406.1	0.91761	372.5	373.0	398.8	397.6
25.5	0.3620E-03	408.8	411.7	0.91770	374.9	375.5	403.8	402.6
30.6	0.3578E-03	413.8	416.7	0.91778	377.5	378.2	408.6	407.3
35.7	0.3536E-03	418.5	421.6	0.91791	380.2	381.1	413.1	411.9
40.8	0.3502E-03	422.8	425.8	0.91803	383.0	384.1	417.2	416.1
45.9	0.3469E-03	426.7	429.8	0.91820	385.9	387.2	421.0	420.0
51.0	0.3443E-03	430.0	433.0	0.91838	388.9	390.3	424.3	423.4
56.0	0.3420E-03	432.8	435.8	0.91861	391.8	393.4	427.1	426.4
61.1	0.3406E-03	435.0	438.0	0.91887	394.7	396.4	429.4	428.9
66.2	0.3394E-03	436.6	439.4	0.91918	397.4	399.4	431.1	430.8
71.3	0.3384E-03	437.5	440.1	0.91955	400.1	402.2	432.2	432.2
76.4	0.3384E-03	437.8	440.3	0.92000	402.6	404.9	432.6	432.9
81.5	0.3384E-03	437.3	439.6	0.92056	404.9	407.3	432.5	433.0
86.6	0.3394E-03	436.3	438.3	0.92126	406.9	409.5	431.7	432.6
91.7	0.3409E-03	434.5	436.3	0.92221	408.7	411.4	430.3	431.4
96.8	0.3425E-03	432.1	433.7	0.92350	410.2	412.9	428.3	429.8
101.9	0.3454E-03	428.7	429.9	0.92570	411.4	414.2	425.3	427.1
107.0	0.3452E-03	429.1	430.2	0.92637	412.5	415.3	425.8	427.7

are plotted in figure 6 as functions of axial position or elevation. The average helium 3 density is given in figure 7 as a function of axial position. A comparison of figures 6 and 7 shows that the average gas density is inversely proportional to the average gas temperature. At a gas pressure of 41 newtons per square centimeter, the total mass of helium 3 in an annulus is 21.9 milligrams.

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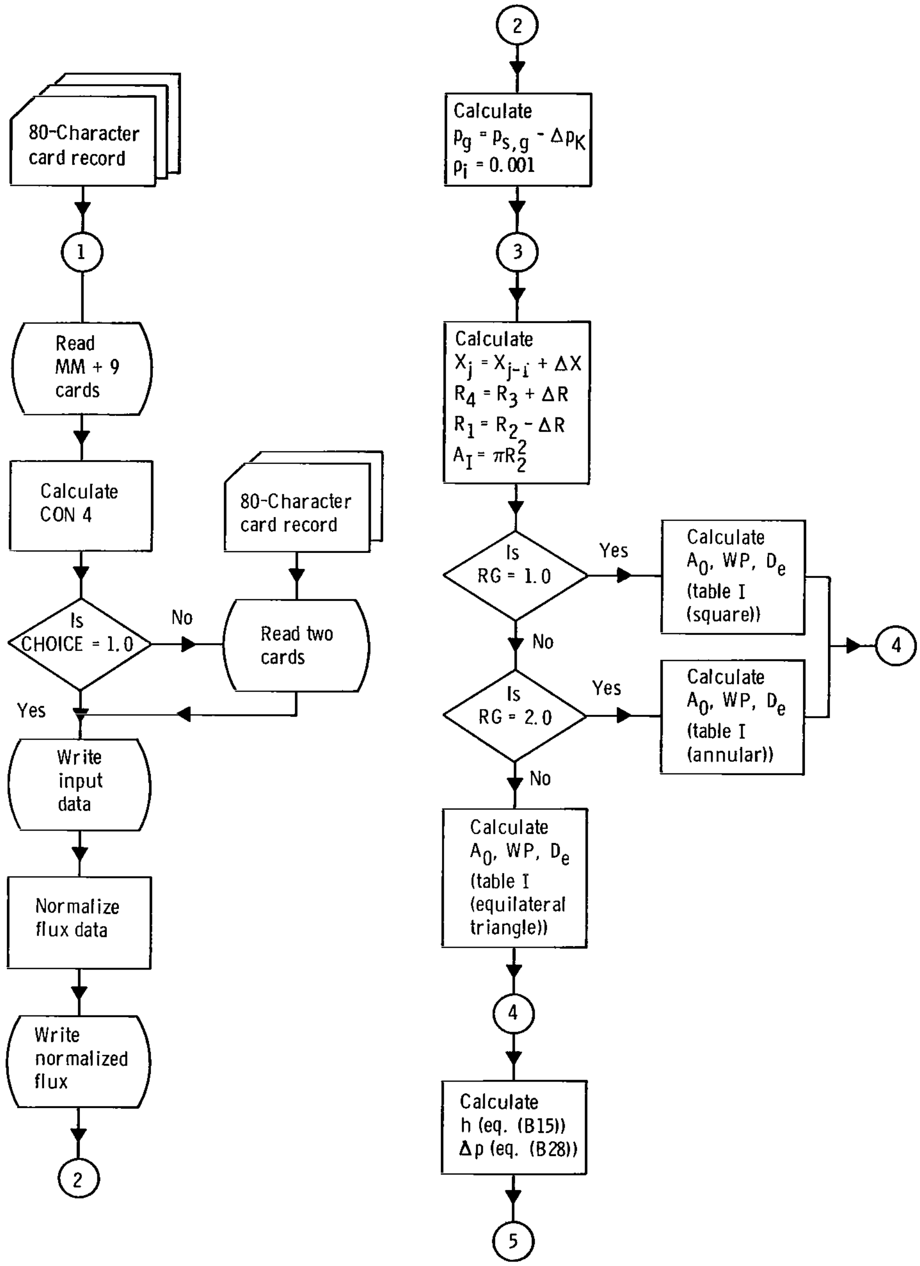


Figure 1. - Program flow sheet for STADDIG.

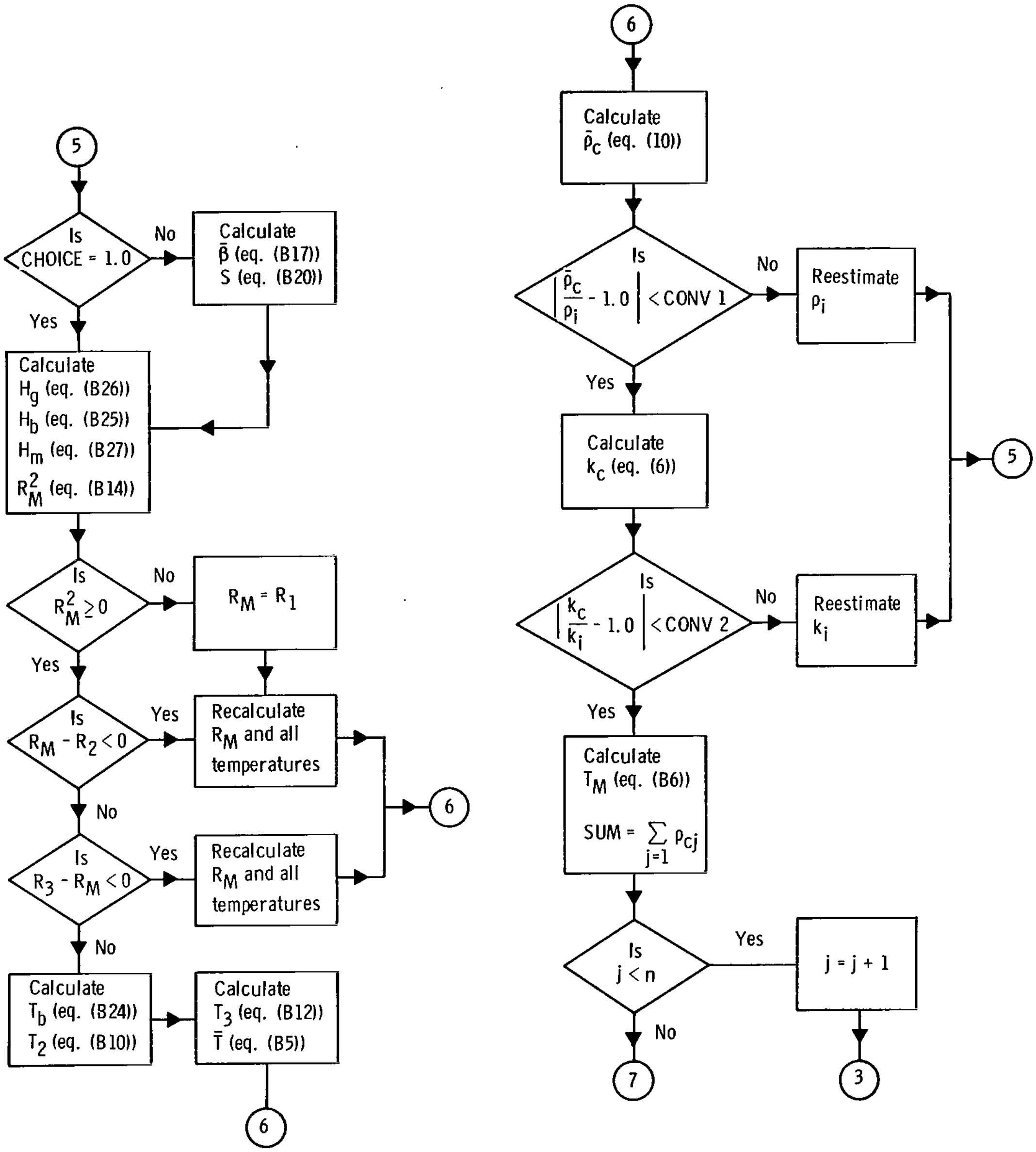


Figure 1. - Continued.

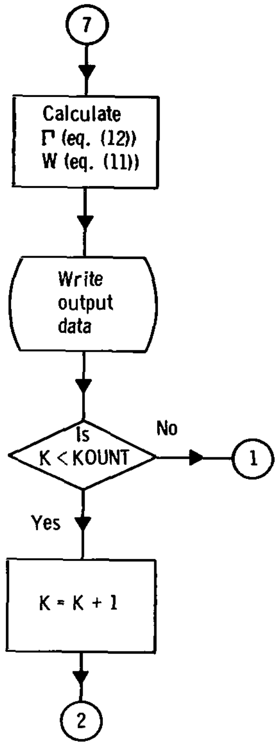


Figure 1. - Concluded.

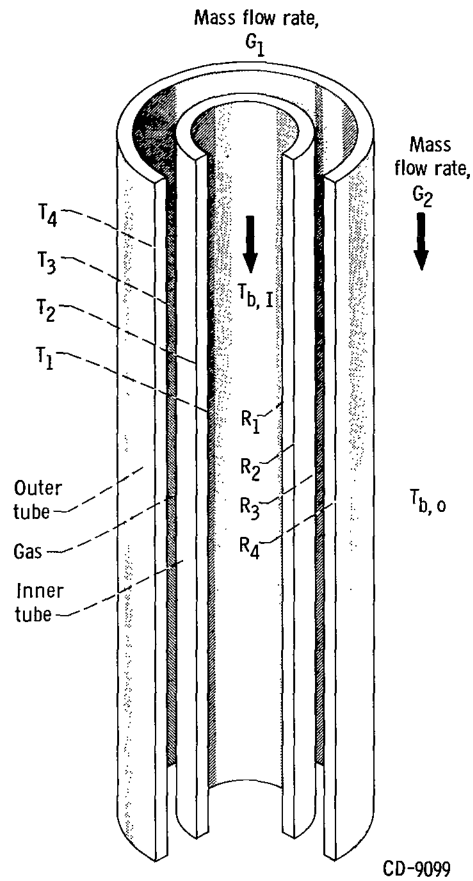
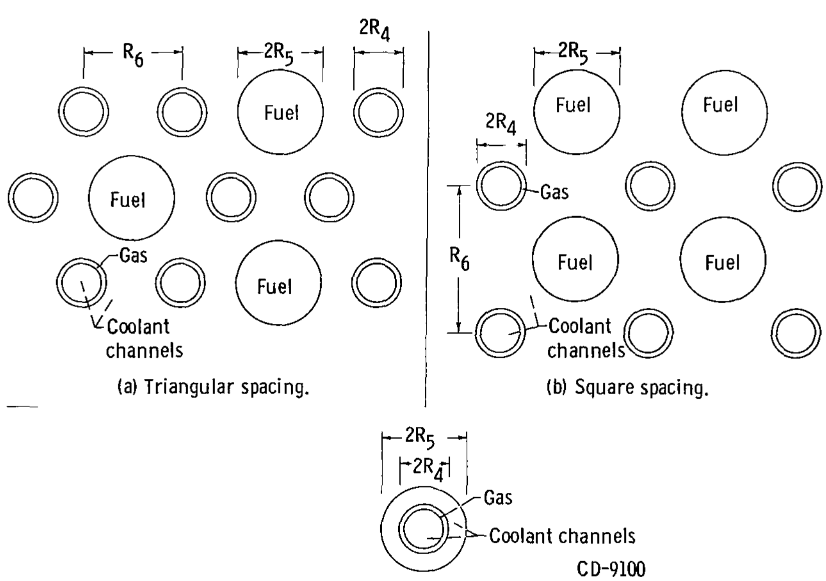


Figure 2. - Heat-transfer model.



(c) Annular spacing.

Figure 3. - Geometric configurations.

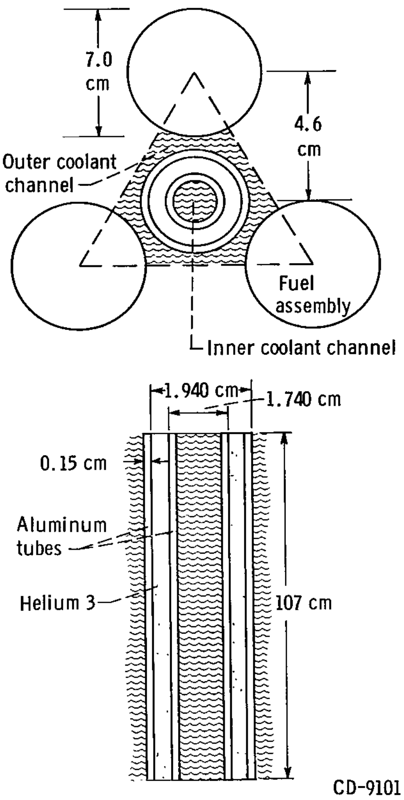


Figure 4. - Reactor conditions for sample problem. (Drawing not to scale.)

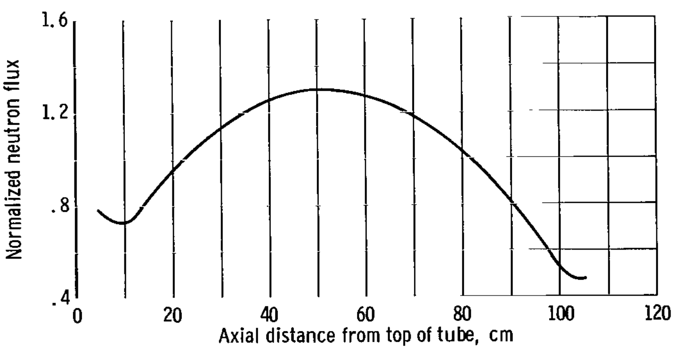


Figure 5. - Axial distribution of neutron flux.

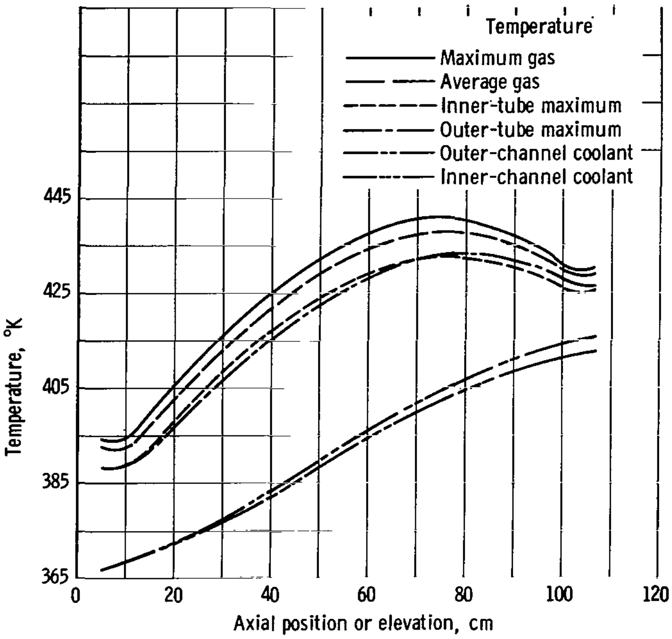


Figure 6. - Axial temperature distributions in control element containing helium 3.

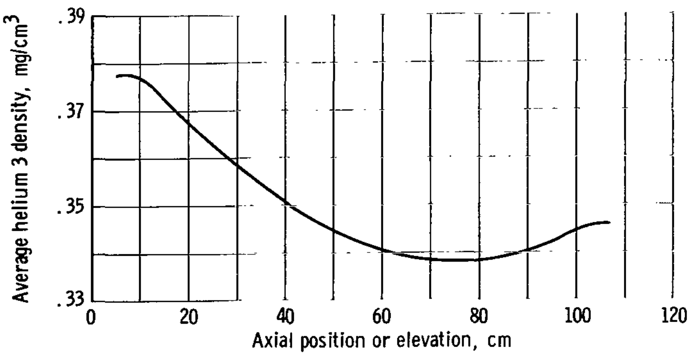


Figure 7. - Axial distribution of helium 3 density in annulus.

NASA-Langley, 1967 —— 22 E-3774

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